VISUALIZATION AND IMAGING METHODS FOR FLAMES IN MICROGRAVITY

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Introduction

The visualization and imaging of flames has long been acknowledged as the starting point for learning about and understanding combustion phenomena. It provides an essential overall picture of the time and length scales of processes and guides the application of other diagnostics. It is perhaps even more important in microgravity combustion studies, where it is often the only non-intrusive diagnostic measurement easily implemented. Imaging also aids in the interpretation of single-point measurements, such as temperature, provided by thermocouples, and velocity, by hot-wire anemometers. This paper outlines the efforts of the Microgravity Combustion Diagnostics staff at NASA Lewis Research Center in the area of visualization and imaging of flames, concentrating on methods applicable for reduced-gravity experimentation. Several techniques are under development: intensified array camera imaging, automated object tracking hardware and software, reactive Mie scattering, infrared emission imaging and two-dimensional temperature and species concentrations measurements. A brief summary of results in these areas is presented and future plans mentioned.

Qualitative Visualization

In many microgravity combustion studies, the systems of most interest lie near the limits of flammability, ignition, or stability, and typically have a dim, blue flame. Difficulties in detecting and imaging these flames using conventional photographic media or video cameras motivate the examination and demonstration of advanced imaging techniques. One approach we have explored is the use of intensified array cameras based on both charge injection device (CID) and charge coupled device (CCD) arrays. The camera contains a microchannel plate intensifier consisting of a photocathode, which converts the photons entering it from the lens into electrons; a microchannel plate, which multiplies the number of electrons; and a phosphor anode, which converts the electrons back into photons. The luminous sensitivity of the camera is increased thereby as much as four orders of magnitude and allows a faceplate illuminance of 10^{-6} to 10^{-5} lux to be detected. Photocathodes sensitive in the visible to near-infrared from 400 to 900 nm and in the ultraviolet from 250 to 650 nm are in use. The output from the camera is available as a RS-170A video signal.

Intensified array cameras have been demonstrated in our 1-g laboratory by imaging several combustion systems, specifically, dilute premixed hydrogen flames, low-pressure gas jet diffusion flames, premixed Bunsen-type flames, solid surface, and low-pressure droplet burning. Results have been obtained using both the visible to near-infrared and ultraviolet photocathodes. Examples of some of these flames are shown in Fig. 1 and 2. Dilute mixtures of hydrogen and air (7% hydrogen) have been imaged by both cameras without the addition of a Halon colorant, previously needed to detect the flames using photographic film. The image shown in Fig. 1, obtained with the visible to near-infrared camera, is stronger than that obtained using the ultraviolet camera. The cameras are detecting light from different emitters: the visible to near-infrared detects the emission in the near-infrared from the hot water produced in the flame, but the ultraviolet camera detects light from the OH radical centered at 308 nm.

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The camera is also able to detect a small, laminar, hydrogen gas jet diffusion flame burning at a total pressure of 100 Torr, which is invisible to the eye. Both cameras have also imaged premixed Bunsen-type methane flames with bandpass filters. Several images of this flame are shown in Fig. 2.

In a reduced-gravity demonstration, an intensified CID camera imaged weakly luminous flames spreading over thermally thin paper samples aboard the NASA Learjet [1]. The camera observed the flames for ashless filter paper samples and laboratory wiper samples burning in quiescent, 21 and 18 percent oxygen environments. Most of the flames would have been difficult to detect using film. Attempts in 1-g to use lower pressure and higher oxygen concentrations to emulate the reduced-gravity combustion were not successful as the flames burned much brighter in 1-g, pointing out the dramatic changes which occur upon greatly reducing buoyant convection. In another reduced-gravity use, premixed hydrogen gas mixtures similar to those in Fig. 1 were imaged using an intensified CCD camera aboard the NASA KC-135A [2]. Heretofore unseen and unpredicted flame structures and behaviors were observed. The use of such a camera is now being planned for a proposed space-flight experiment to further study these flames.

Another type of qualitative visualization which provides an indication of the location of the reaction zone in a flame is reactive Mie scattering [3]. Laser light scattering centers are created *in situ* by seeding the flame with a reactive compound, such as titanium tetrachloride. This material reacts with water produced in the reaction zone to produce particles of titanium dioxide. The light scattered from a laser light sheet by the particles can be imaged onto a detector. This technique was tried in 1-g for small methane and hydrogen gas jet diffusion flames having flow rates typical of those used in previous microgravity studies. With an argon ion laser for the light sheet source, a narrow-band interference filter at 488 nm, and a intensified CID camera, a significant amount of seed, ~0.1% of the total fuel flow of 160 sccm, was required to obtain an acceptable signal. A change in flame color suggested an effect on flame chemistry, although flame emission spectra were not quantified. Others have used this technique for the visualization of transitional and turbulent flame structures. Those flames had much higher total flow rates, and were only slightly perturbed by the production of the particles and hydrogen chloride, as evidence by a 60 K depression in the stoichiometric temperatures [3]. The formation of hydrogen chloride and subsequent problems with corrosion and venting will likely preclude the use of this technique in the reduced-gravity facilities, although the use of titanium isopropoxide, which does not produce HCl, is being considered. The use of a pulsed laser source for the light sheet is also being explored, as a means to reduce the background flame emission by gating of the camera to match the laser pulse length.

A major advancement in our capability to use non-optimum film or video images has been the development of a system for the automatic and semiautomatic tracking of objects on film or video tape using a color image processing and object tracking workstation [4]. The system components include a 16-mm film projector, a lens system, a video camera, an S-VHS tapedeck, a frame grabber, and computer-based storage and output devices. Tracking software has been developed to control the system via a computer. The program controls the projector or tapedeck frame incrementation, grabs a frame, image processes it, locates the feature of the object being tracked, and stores the coordinates in a file. The image processing that can aid in the analysis include selective thresholding, gradient and Laplacian filtering for edge detection, line histogram equalization to eliminate an uneven background, and multi-frame averaging. Applications of the system include tracking the propagation of a flame front over condensed-phase materials in microgravity and tracking the movement of a liquid-gas interface from a nearly invisible meniscus. The system also can be used for objective color characterization, such as that exhibited by the different color regions in a methane diffusion flame.

Infrared Emission Imaging

As mentioned above, many of the interesting flames found in microgravity studies are too weakly luminous in the visible portion of the spectrum to be easily seen by conventional film-based or video cameras. Although flames are not in complete thermal equilibrium, a large portion of their radiant energy is emitted as infrared radiation [5], which may be detected by infrared-sensitive devices. Visibly-clear flame gases emit in an infrared spectrum of discrete bands from hot combustion products. The mid-infrared emission occurs primarily from carbon dioxide at 2.8 and 4.3 microns and from water at 1.8 and 2.7 microns. The intensities and shapes of the bands depend on the temperature and composition of the combustion products. Measurements of temperature and concentration contours are desirable for making a comparison between the observed flame and model calculations. Fuel-rich mixtures also may contain soot, which emits broad-band radiation.

Until recently, the most common infrared cameras have been either single element or linear array detectors. For best detectivity, the detector element is cooled to cryogenic temperatures. The detector element may be combined with scanning optics to provide an expanded field-of-view and spatially-resolved images. These cameras possess some disadvantages for combustion diagnostics. For example, they contain moving parts in the scanning optics, which often produce a smeared image of a moving object. In addition, they are useful primarily for thermography of solids or liquids such as pools, which have known or measured emissivities, and not as useful for the detection of gas phase emissions because of the non-grey-body emissivities. They often give data output in temperature units rather than the intensities needed for spectral data analysis.

Newly developed cameras such as those based on platinum silicide or indium antimonide possess many qualities making them suitable for application to combustion diagnostics. They are sufficiently sensitive in the near- and mid-infrared spectral region of 1 to 5 microns to detect the infrared emissions and are true two-dimensional, solid-state, staring arrays. The output may be digital or a RS-170 video format suitable for display on a monitor, digitizing by a frame grabber, or recording on videotape for immediate playback or future analysis.

A low-resolution (128 x 128 pixels) platinum silicide camera has been used for our laboratory studies, although cameras with higher pixel counts are available at a significantly higher cost. The camera has a 100 mm focal length lens and an integration time of 1/30 sec. The bandpass filter supplied with the camera transmits wavelengths from 3 to 5 microns. An image obtained of a methane diffusion flame is shown in Fig. 3. The flame height as visible to the eye is 5 cm, but the camera is able to detect the structure of the invisible hot gases rising several cm above the flame.

Experimental work to obtain spatially- and spectrally-resolved infrared images has occurred in two areas. First, a monochromator having an infrared grating and detector has been acquired and will be used to acquire an infrared emission spectrum of the flame in order to identify the wavelength regions of interest. Some bandpass filters have already been identified and will be used to obtain spectrally-filtered images. Second, a contract under the Phase I Small Business Innovative Research program has resulted in the design and construction of an infrared imaging spectrometer. The spectrometer has demonstrated the ability to resolve wavelengths from 3 to 5 microns with 15 nm resolution for a propane/air torch flame.

The inversion of spatially- and spectrally-resolved infrared images to obtain species concentrations and temperature profiles still remains a major effort. It involves two parts: computerized image reconstruction using tomographic algorithms, and the analysis of infrared emission spectra. The medical industry has advanced the development of tomographic algorithms, which are being applied to combustion data [6]. Two main classes of algorithms, Fourier transform and iterative, are used. The analysis of infrared emission spectra is complicated by the fact that infrared emitting species also absorb and the path of the light from the emitter to the detector must be considered. Computer codes, such as the Aerodyne Radiation Code (ARC), have been developed to predict infrared spectra [7]. The

ARC calculates the infrared spectral signatures of rocket and aircraft exhaust plumes along a line-of-sight and includes molecular and particulate emission and absorption and chemiluminescent emission. Such codes may be useful for microgravity combustion. One of the goals of this research is to investigate combining code such as this with tomographic algorithms for simple combusting systems to obtain three-dimensional species and temperature profiles.

The acquisition of images of known emissivity radiators, such as soot or thin ceramic fibers placed in the flame, offers another possibility for obtaining temperature field measurements. The emission as seen through two or more narrow-band filters is fit to a Planck distribution function to yield a ratio temperature. Soot measurements have been studied extensively in the past and a body of literature exists for reference. Point and line measurements using thin ceramic fibers have been reported using fast response, near-infrared linear arrays [8]. Ceramic fiber grids are already being used successfully in the drop tower for the qualitative assessment of the temperature distribution in gas-jet diffusion flames and an individual fiber is being used as a tether and temperature indicator for an isolated, combusting droplet.

Two-dimensional Temperature and Species Measurements Using a Solid-State Laser Source

Two-dimensional measurements of temperature and species concentrations in combusting systems are of special value [9]. While various single-point (in time and space) methods have received considerable attention, knowledge of the instantaneous overall flow field is preferable, especially in turbulent or rapidly-evolving flow fields. The acquisition of many single data points does not always allow reconstruction of the flow field and is restricted in microgravity combustion studies by the limited experimental time and/or laboratory availability. Both molecular Rayleigh scattering and planar laser-induced fluorescence (LIF) have been used as imaging techniques and to provide temperature and species concentrations measurements.

Rayleigh scattering is an elastic scattering process, whose signal depends on the incident laser frequency, the molecular composition, and the number of scatterers. As the frequency of the light detected from all scatterers is the same as that of the incident laser light, the technique lacks species specificity. It suffers from interference from scattered laser light and Mie scattering from particles, but has a relatively high signal strength compared to other laser-based diagnostics. Rayleigh scattering is used for total density measurements, which can be related to temperature. LIF is used to detect an atom or molecule detecting fluorescence from an excited electronic state following the absorption of laser light. Species specificity is provided by tuning the laser wavelength to an absorption transition and selecting the observation wavelength, which may be the same as or shifted from the laser wavelength. Key combustion intermediates found near the flame front in the parts per thousand to parts per million, such as OH and CH, can be imaged using a planar light sheet. Quantitative measurements can be made but are more difficult. LIF can be used to measure temperatures by scanning the laser over several rotational transitions originating from different rotational levels having temperature-dependent populations.

Both techniques benefit from a laser source with a short pulse length and high peak power. LIF requires a tuneable laser source in the blue and ultraviolet. Rayleigh scattering measurements also benefit from a tuneable source, since the wavelength may be tuned away from flame emissions. Most currently-available laser sources used for laboratory-based, two-dimensional measurements are unsuitable for low-gravity and space flight applications for a variety of operational and safety reasons. Dye lasers use flammable solvents and toxic laser dyes which have only a finite lifetime. Excimer lasers use corrosive gases such as hydrogen chloride or fluorine, which must also be changed regularly. These lasers are also quite large and require much operator interaction.

The rapid development of pulsed, solid-state lasers based on titanium:sapphire offers a probable solution to the problems outlined above. Laser action in the titanium:sapphire crystal was first reported in 1982 and the material was developed rapidly into a laboratory device [10]. Continuous-wave lasers have been available from several vendors for several years and, recently, pulsed laser systems were introduced. The titanium:sapphire laser is broadly tuneable from 700 to 1000 nm. The production of blue and ultraviolet light useful for combustion diagnostics from such a laser by frequency conversion was demonstrated under a Phase I SBIR contract monitored by NASA Lewis in 1990 [11].

Acquisition of a laser system capable of performing the diagnostic measurements described above is in progress. Development and demonstration of these techniques using this laser source is an important step towards bringing the level of diagnostics commonly available to microgravity combustion research up to that available in other government, university, and industrial laboratories. The system will serve as a prototype for the future and will place the development of microgravity combustion diagnostics at the forefront of this rapidly evolving technological area.

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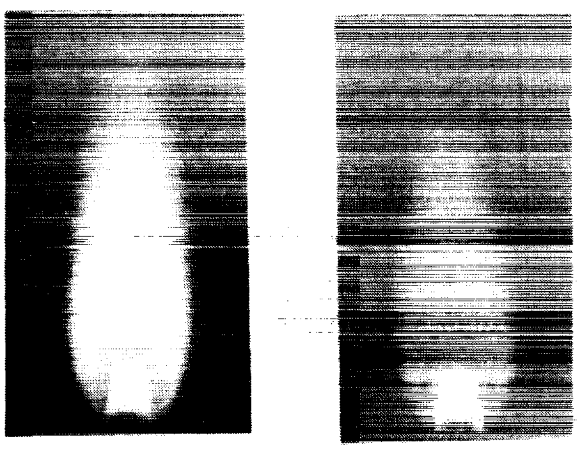
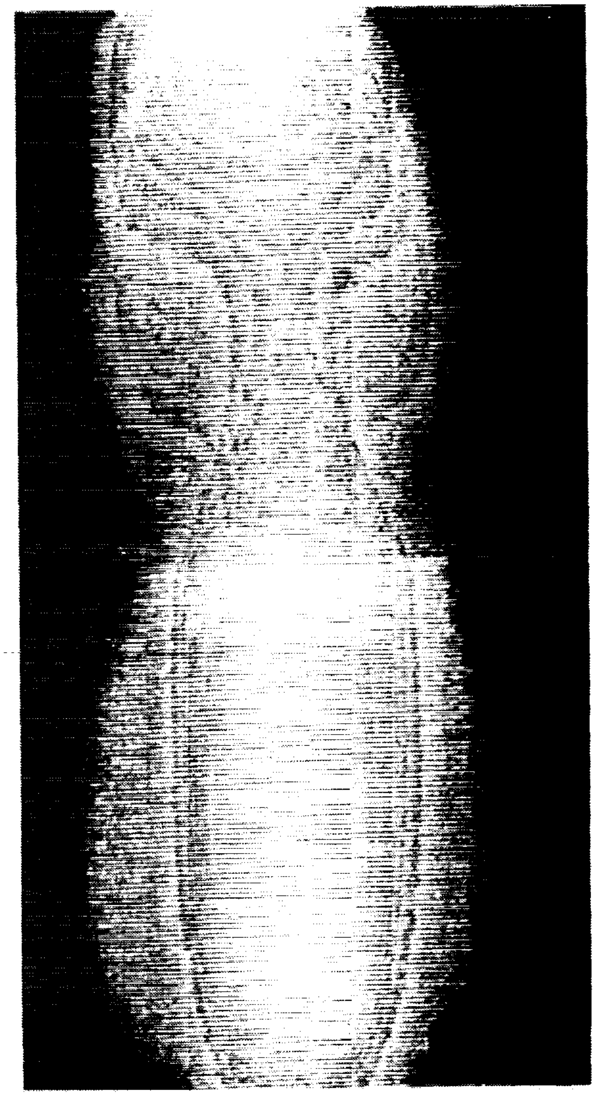
Figure 1. Image of a 7% hydrogen in air premixed flame obtained using a visible to near-infrared intensified array camera. The image is at 0.2 sec following spark ignition in a closed vessel.



a) b)

1 cm

Figure 2. Images of a Bunsen-type, methane/air jet flame using an ultraviolet to visible intensified array camera. The images are obtained using interference filters centered at a) 307 nm and b) 431 nm and having a bandpass width of 10 nm before the camera.



1 cm

Figure 3. Image of a methane gas jet diffusion flame obtained using a platinum silicide infrared array camera.